A cost benefit analysis of fuel cell electric vehicles

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Content

Executive summary

This study develops a consistent framework to compare FCEV with gasoline ICE (ignition combustion engine) and applies this framework to the German market over the period 2015-2050. As such it provides for:

- The formulation of a proper cost benefit analysis, including the definition of the abatement cost for the hydrogen technology;
- The simulation of the results under various technological and cost assumptions;
- The identification of the major conceptual issues to facilitate analytical developments.

The sources used in the analysis are based on an update of previous industry studies.

The main conclusion is that FCEV could be a socially beneficial alternative for decarbonizing part of the projected German car park at the horizon 2050. The corresponding abatement cost would fall in the range of 50 €/t CO2 to 60 €/t CO2. This range is higher than the current estimate for the normative cost of carbon as expressed in Quinet (2009 and 2013), which is around 30€/t in 2015. Still the gap is not out of hand. We identify the market and cost conditions that would shorten the gap.

The methodology used in this study could be expanded to integrate two pending issues noted in the literature for the successful deployment of FCEV:

- Making the deployment for FCEV endogenous and depending on the public and private instruments that could induce the decreasing of costs and the acceptance of the FCEV technology by consumers.
- Designing an appropriate institutional framework to promote cooperation for manufacturing FCEV, producing carbon free H2 and investing in the distribution of H2. The initial sunk costs necessary for investment cannot be recouped through pure market equilibrium behavior.

This study already provides an order of magnitude to quantify these issues.

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Scope of the study

Nowadays approximately 25% of the world CO2 emissions are attributable to the transportation system (Eurostat, 2009). Out of this percentage, 75% is caused by passenger cars and trucks. According to current trends the number of cars may double until 2050 due to population and income increases (IEA-International Energy Outlook report, Feb 2013). The decarbonisation of the transport system is one of the key challenges for mitigating climate change.

A number of studies have explored the possible technological innovations and the associated economic conditions that could lead to the emergence of new power-trains such as battery electric vehicles (BEV), fuel cell electric vehicles (FCEV), hybrid vehicles… A survey of these studies is provided in appendix 1. Among them a study (McKinsey & Company, 2010) developed scenarios for the deployment of PHEV, BEV and FCEV in Europe over the period 2013-2050. This study involved a group of companies (among which car manufacturers, oil and industrial gas companies, electricity producers), the European Fuel Cells and Hydrogen Undertaking, with the support of the McKinsey consulting firm (McKinsey & Company, 2010). In 2012, Bruegel and the European School for Management and Technology reviewed the potential benefits of a new energy and transport system and revisited the economic rationale for public action using FCEV as an illustration (Zachmann et al., 2012).

The objective of the current study is to provide a simple model that builds on these studies. It compares FCEV with gasoline ICE (internal combustion engine) for the German market, without taking into account any indirect incentive tools (carbon tax on transport emissions) nor direct incentive tools for FCEV (tax reduction, subsidies, bonus…) except fuel tax exemption for H2 (such as TIPP in France). As such it provides a consistent framework for:

- The formulation of a proper cost benefit analysis, including the definition of the abatement cost for the hydrogen technology;
- The simulation of the results under various technological and cost assumptions;
- The identification of the major conceptual issues to be addressed in analytical developments.

This framework may be a good starting point for a number of extensions (comparing portfolios of power-trains, other markets areas…).

Methodology

This cost benefit analysis of FCEV versus gasoline ICE vehicles:

- Starts from a scenario characterized by an exogenously given market size for the deployment of FCEV over the period 2015-2050, using the German market as an illustration;

- Generates the various cost components associated with this scenario (manufacturing, fuel, infrastructure);

- Compares these costs with a counterfactual scenario in which gasoline ICE vehicles would be used instead of FCEV;

- Compares the CO2 emissions of both scenarios taking into account the technologies used to produce hydrogen at different time periods.

A number of static and dynamic indicators are derived from this model:

- For any given year the total cost of ownership for the consumer (TCO) of one car unit of FCEV versus ICE is obtained based on the associated capital (given the life time of the car) and the operating costs at that year; the year (if any) at which the two TCO cross is derived;

- The yearly static abatement cost defined as the ratio of the delta TCO divided by the delta CO2 emissions for that year; this cost is expected to decline over time due to economies of scale and learning by doing in the cost components;

- The total net discounted cost of the FCEV scenario versus the ICE scenario over the 2015-2050 period;

- The dynamic abatement cost based on this total net discounted cost and the delta CO2 emissions for year 2050.

Appendix 2 provides the data used for the various cost components, and the sources used to generate this data. Appendix 3 details our economic reasoning, including the assumptions regarding the discount factor, the notions of levelized costs and abatement costs.

The base case: summary of data and the associated cost benefit analysis

Table 1 gives a summary of the data used for the base case and Table 2 gives the associated results.

Table 1 Summary of the data for the base case

Simplified Data Sheet	Unit	**2015**	**2020**	**2025**	**2030**	**2050**
Market size (car life time 10 years)	#1000	1	95	453	1350	7500
Manufacturing costs						
FCEV purchase cost (19% TVA is not included)	kú	60,0	37,9	32,4	28,9	23,1
ICE purchase cost (19% TVA is not included)	kú	22,0	21,4	21,3	21,1	20,5
Fuel costs						
FCEV						
Hydrogen production cost (delivery cost to HRS included)	ú/kg	7,0	5,8	6,1	6,3	6,8
Hydrogen consumption per 100 km	kg/100km	0,95	0,87	0,84	0,80	0,70
ICE						
Gasoline price per litre (TVA 19% is not included)	ú/l	1,30	1,35	1,40	1,46	1,71
Gasoline consumption per 100 km	l/100km	7,04	6,2	4,97	4,88	4,8
Infrastructure costs						
Number of HRS	#	40	220	926	2234	9257
Capital cost per unit of car	kú	62,24	2,39	2,02	1,65	1,18
Opex per unit of car	kú	6,22	0,24	0,16	0,13	0,09
CO2 emissions						
Hydrogen	kgCO2/100km	9,0	6,2	5,0	3,8	1,7
Gasoline	kgCO2/100km	19,8	17,4	14,0	13,7	13,5

Market size refers to the FCEV park. Manufacturing costs are embedded in the purchase cost of the car (development and capital expenditures are assumed to be integrated in this cost). A yearly maintenance cost is added to the purchase cost (8% for FCEV and 10% for ICE).

Fuel costs for hydrogen depend on the technology to produce hydrogen (development and capital expenditures are assumed to be integrated in this cost). The logistics cost to the hydrogen refueling station (HRS) is added to the production cost. Gasoline price is the delivery price at the retail station; it depends on the oil price in the world market. The state tax on imported petroleum is included.

The infrastructure cost for hydrogen is derived from the required network to deliver the total hydrogen consumption at every time period (with lower capacity utilization rates for the early years) and on the associated capital and operating expenditures.

Table 2 Cost analysis for the base case

Cost benefit analysis						
	Unit	**2015**	**2020**	**2025**	**2030**	**2050**
Delta purchase and maintenance cost	kú/year	7,6	3,0	1,9	1,2	0,1
Delta fuel cost	kú/year	-0,4	-0,5	-0,3	-0,3	-0,5
Infrastructure for H2	kú/year	13,8	0,3	0,2	0,1	0,1
Delta TCO per vehicle	kú/year	21,1	2,8	1,8	1,0	-0,3
TCO converge in	year	**2042**				
Total discounted delta cost from 2014 to	Mú	20 260	1 897	5 921	11 926	17 495
CO2 emissions avoided	t/year	1,62	1,68	1,35	1,49	1,76
Total CO2 avoided	Mt	161				
Abatement cost						
Static approach	ú/t	13 023	1 662	1 321	667	-196
Dynamic approach	ú/t	53				

The main conclusion for the base case: a reasonable range for H2 abatement cost

Consider first the cost aspect (Figures 1 and 2). The TCO for FCEV crosses the one for ICE on year 2042. The delta cost of TCO starts at a very high level (21 k€ in 2015), sharply drops from 2015 to 2020 and then drops more slowly from 3 k€ in 2020 to 1 k€ in 2030 to remain in the range .5 k€ to -.5 k€ thereafter. The infrastructure cost rapidly declines after the first three years. While it represents a high absolute initial investment cost, the yearly equivalent for one car unit drops to .2 k€/year after 2020. The relatively high hydrogen production cost is compensated by the higher efficiency of FCEV so that there is a benefit over ICE in terms of fuel cost (recall that no fuel tax is incurred on hydrogen) that more than compensates the infrastructure cost. The manufacturing cost for FCEV starts quite high and experience takes time to accumulate, so this cost remains the main cost component over the whole horizon.

Figure 1 Analysis of the cost components in the delta TCO for one car unit (2015-2020)

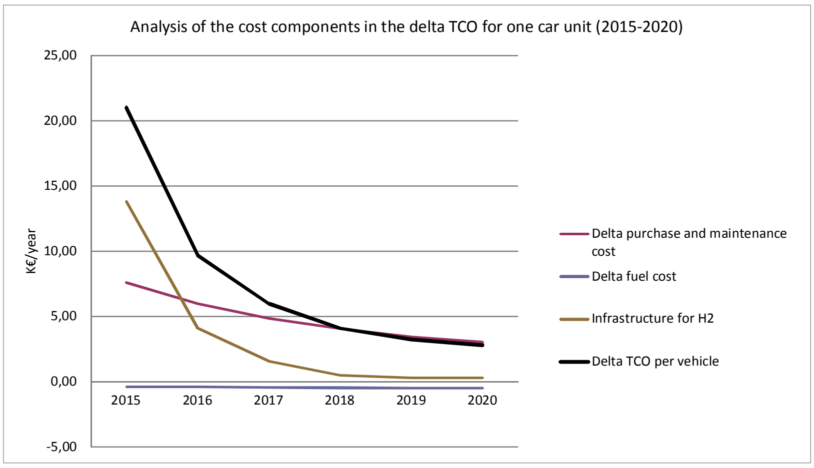
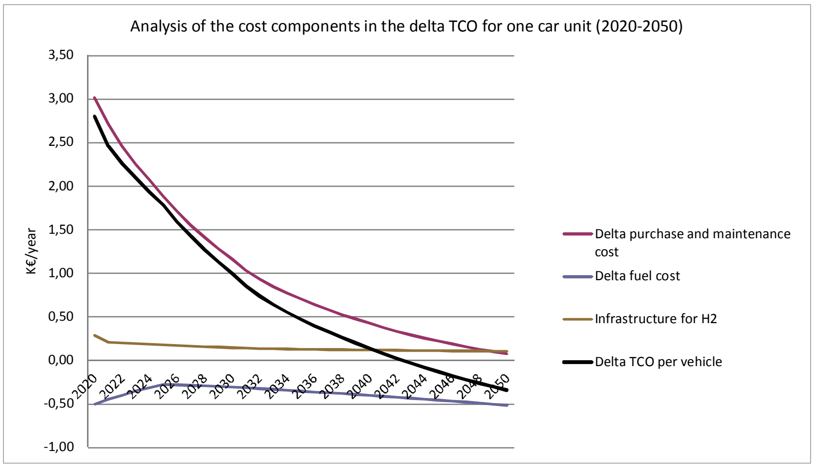


Figure 2 Analysis of the cost components in the delta TCO for one car unit (2020-2050)



Going from the cost per unit of car to the full cost brings some interesting insights for the deployment scenario: the unit delta cost is now multiplied by the total FCEV car park (taking into consideration the respective life times of cars and HRS). The discounted costs are displayed in Table 3. The costs are discounted from year 2014 using a social discount rate at 4 % (all financial figures are in € 2014).

Table 3 The total net discounted cost for the deployment of FCEV versus ICE

Total discounted delta cost (Mú)	**2015-2020**	**2021-2030**	**2031-2050**	**2015-2050**
Delta purchase and maintenance cost	1 727	9 733	14 564	26 024
Delta fuel cost	-78	-1 131	-12 877	-14 086
TIPP	102	1 918	16 305	18 325
Infrastructure for H2	248	1 426	3 882	5 556
Total with TIPP excluded	1 999	11 946	21 875	35 820
Total with TIPP included	1 897	10 028	5 569	17 495

A preliminary comment concerns the role of the interior tax on imported petroleum (TIPP). We consider that hydrogen should be given the benefit of contributing to the reduction of petroleum imports, so that this tax should not be applied. Still, as can be seen in Table 3, the difference between the total discounted with no TIPP (TIP excluded in the gasoline price) and with TIPP (TIPP included in the gasoline price) corresponds to the associated tax revenue. This amount is significant and a financing issue may arise for the State during the full deployment phase (2031-2050).

Over the whole period (2015-2050) the total discounted delta cost (TIPP included) amounts to 17.495 billion euros. The breakdown of this figure over the three periods 2015-2020, 2021-2030 and 2031-2050, and over the three cost components shows that:

- The main expenses would occur from 2021 to 2030 that is 10.028 billion euros.
- From then on, the negative delta fuel cost per unit of car generates a substantial excess that increases as the car park increases, so much that it compensates part of the two other components in the period 2031-2050; still the discounted cash flow over that period remains negative;
- This emphasizes the complementarity nature of the three cost components (manufacturing of FCEV, H2 production, H2 distribution).

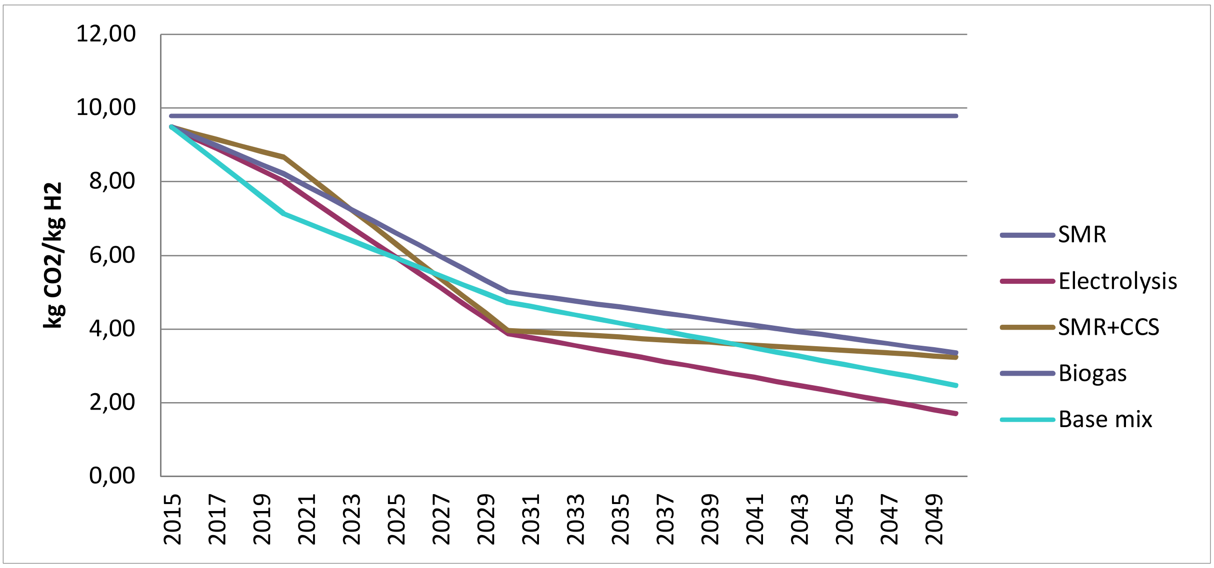
Consider now the emissions aspect. It depends on the relative energy efficiencies of FCEV and ICE (ICE improves by 30% over 2015-2030, and only by 2% over 2030-2050; FCEV improves by 16% and 13% respectively over these time periods), and on the portfolio of technologies used to produce H2. We consider four potential technologies, a mature one and three which are still under development and which would be necessary to decarbonize the production process:

- The current mature technology, steam methane reforming (SMR) using natural gas
- SMR using natural gas with carbon capture and storage (SMR+CCS)
- SMR using Biogas

- Electrolysis with renewable electricity

From these technologies we construct five technological scenarios: a pure SMR scenario; three scenarios in which one of the three new technologies is progressively introduced in substitution to SMR; our base case in which all the new technologies are combined. Figure 3 compares the emissions of these five scenarios. The reduction of emissions will provide increasing benefits to society as the FCEV car park increases from 1.350 million units in 2030 to 7.500 million units in 2050.

Figure 3 CO2 emissions in the production of hydrogen



Using the cost figures and the emissions we derive the abatement costs. The static abatement cost drastically declines over the period, say from 1 442 €/t in 2025 to 781 €/t in 2030, to become negative after 2042. This drastic decline shows the limit of such a static indicator in presence of learning rates and economies of scale. The dynamic indicator is more meaningful. It is derived for the deployment of the car park until 2050, neglects the interim gains in emissions but assumes that the avoided emissions will indefinitely remain after 2050. As proved in the Appendix 3, this can be considered as an extension of the static abatement cost to assess the benefit of an investment program with significant learning rates and economies of scale. This approach leads to an abatement cost of 53 €/t, which may be compared to the normative values of CO2 prices estimated to be around 30€/t (cf. appendix 3).

The main conclusion from these results is that FCEV should be considered as a socially profitable alternative to explore for the decarbonisation of the transport system by 2030 - 2050.

Robustness of the main conclusion with respect to major uncertainties

In this section the robustness of our main conclusion is first tested with respect to three major uncertainties:

- The availability of a new decarbonized production technology for hydrogen;
- The oil price;
- The acceptability of FCEV by the consumer and its impact on the deployment of FCEV.

Table 4 tests the technological uncertainty in producing hydrogen. If none of the three new technologies currently under development emerges, there will be a substantial increase in the abatement costs. The decrease in the total discounted cost due to the exclusive use of SMR (cheaper than the 3 other ways) does not compensate the decrease in the total CO2 avoided. Moreover, it does allow Europe to reach its objective of decreasing by 95% the GHG emissions related to road transportation by 2050. However, if at least one of the three new technologies emerges, whatever it is, our main conclusion remains valid.

Table 4 The technological uncertainty in producing hydrogen

H2 production technology						
		Base mix	**SMR+nat gas**	**SMR+CCS**	**SMR+Biogas**	**Electrolysis**
TCO converge in	year	2042	2040	2042	2041	2042
Total discounted delta cost from 2014 to	Mú	20 260	17 951	19 870	19 740	20 597
Total CO2 avoided	Mt	161	92	159	154	170
Dynamic approach	ú/t	53	74	54	53	52

The future oil price is a major uncertainty.[5] We test extreme scenarios around our base case which corresponds to IEA projections. A low oil price (corresponding to a 0% annual growth rate) would increase the dynamic abatement cost from 53 to 68 €/t, as shown by Table 5. However Table 6 shows that a moderate increase in the learning rate in manufacturing (leading to the convergence of manufacturing costs in 2050; FCEV keeping some advantage in terms of maintenance) would be enough to reverse the situation, leading to an abatement cost of 4 €/t! Again we note the impact of the manufacturing cost in driving our results.

Table 5 Scenario with a low oil price

Cost benefit analysis						
	Unit	**2015**	**2020**	**2025**	**2030**	**2050**
Delta purchase and maintenance cost	kú/year	7,6	3,0	1,9	1,2	0,1
Delta fuel cost	kú/year	-0,4	-0,5	-0,2	-0,2	-0,3
Infrastructure for H2	kú/year	13,8	0,3	0,2	0,1	0,1
Delta TCO per vehicle	kú/year	21,1	2,8	1,8	1,1	-0,1
TCO converge in	year	2046				
Total discounted delta cost from 2014 to	Mú	23 062	1 902	5 973	12 170	22 402
CO2 emissions avoided	t/year	1,62	1,68	1,35	1,49	1,76
Total CO2 avoided	Mt	161				
Abatement cost						
Static approach	ú/t	13 029	1 684	1 360	722	-74
Dynamic approach	ú/t	68				

[5] For historical trends in oil prices see http://www.eia.gov/dnav/pet/pet_pri_spt_s1_a.htm. From 2000 to 2014 the oil price (in $2014) increased from 30 to $80/bbl that is at 7%, while it remained flat over the years 1980-2000.

Table 6 Scenario with a low oil price and a high learning rate in manufacturing

Cost benefit analysis						
	Unit	**2015**	**2020**	**2025**	**2030**	**2050**
Delta purchase and maintenance cost	kú/year	7,6	2,6	1,4	0,6	-0,5
Delta fuel cost	kú/year	-0,4	-0,5	-0,2	-0,2	-0,3
Infrastructure for H2	kú/year	13,8	0,3	0,2	0,1	0,1
Delta TCO per vehicle	kú/year	21,1	2,4	1,3	0,5	-0,7
TCO converge in	year	2035				
Total discounted delta cost from 2014	Mú	11 418	1 723	4 994	9 126	1 270
CO2 emissions avoided	t/year	1,62	1,68	1,35	1,49	1,76
Total CO2 avoided	Mt	161				
Abatement cost						
Static approach	ú/t	13 029	1 413	976	357	-391
Dynamic approach	ú/t	4				

Consider now the impact of a high oil price (corresponding to a 4% annual growth rate). As seen from table 7 the dynamic abatement cost would drop from 53 to - 5 €/t. The TCO would converge in 2035 and the total discounted cost would become negative.

Table 7 Scenario with a high oil price (TIPP included)

Cost benefit analysis						
with TIPP	Unit	**2015**	**2020**	**2025**	**2030**	**2050**
Delta purchase and maintenance cost	kú/year	7,6	3,0	1,9	1,2	0,1
Delta fuel cost	kú/year	-0,5	-0,6	-0,5	-0,6	-1,5
Infrastructure for H2	kú/year	13,8	0,3	0,2	0,1	0,1
Delta TCO per vehicle	kú/year	21,0	2,7	1,6	0,7	-1,3
TCO converge in	year	**2035**				
Total discounted delta cost from 2014 to	Mú	14 683	1 877	5 742	11 109	- 1 749
CO2 emissions avoided	t/year	1,62	1,68	1,35	1,49	1,76
Total CO2 avoided	Mt	161				
Abatement cost						
Static approach	ú/t	12 977	1 580	1 191	487	-734
Dynamic approach	ú/t	-5				

Under these conditions excluding TIPP from the cost benefit analysis would still provide reasonable results. Table 8 gives a dynamic abatement cost at 69 €/t.

Table 8 Scenario with a high oil price (TIPP excluded)

Cost benefit analysis						
without TIPP	Unit	**2015**	**2020**	**2025**	**2030**	**2050**
Delta purchase and maintenance cost	kú/year	7,6	3,0	1,9	1,2	0,1
Delta fuel cost	kú/year	0,2	0,0	0,1	0,0	-0,6
Infrastructure for H2	kú/year	13,8	0,3	0,2	0,1	0,1
Delta TCO per vehicle	kú/year	21,7	3,3	2,2	1,3	-0,4
TCO converge in	year	**2044**				
Total discounted delta cost from 2014 to	Mú	25 505	1 983	6 420	13 374	22 708
CO2 emissions avoided	t/year	1,62	1,68	1,35	1,49	1,76
Total CO2 avoided	Mt	161				
Abatement cost						
Static approach	ú/t	13 404	1 966	1 613	888	-249
Dynamic approach	ú/t	69				

Table 9 analyses the third uncertainty: the acceptability of FCEV by consumers either with a slower ramp up or with a quicker ramp up. This would affect the total discounted cost of the deployment and possibly the yearly amount of CO2 saved in 2050. On the one hand a slower deployment starting 2 years later than in the base case and reaching only 7 million cars in 2050 would decrease the deployment cost but at the expense of avoided emissions and result in an abatement cost of 65 €/t. On the other hand a quicker deployment in which a target of 8.0 million cars would be achieved in 2050 would significantly decrease the deployment cost without affecting the avoided emissions in year 2050 giving an abatement cost of 48 €/t. Given that there are large uncertainties on the market conditions that influence the substitution of ICE by FCEV further analysis should certainly be made.

Table 9 The uncertainty about the acceptability of FCEV by consumers

Cost benefit analysis						
with slower ramp up	Unit	**2015**	**2020**	**2025**	**2030**	**2050**
Delta purchase and maintenance cost	kú/year	7,6	4,1	2,3	1,4	0,2
Delta fuel cost	kú/year	-0,4	-0,5	-0,3	-0,3	-0,5
Infrastructure for H2	kú/year	90,4	0,5	0,2	0,1	0,1
Delta TCO per vehicle	kú/year	97,6	4,1	2,2	1,3	-0,2
TCO converge in	year	2044				
Total discounted delta cost from 2014 to	Mú	18 130	759	3 870	8 773	17 070
CO2 emissions avoided	t/year	1,62	1,68	1,35	1,49	1,76
Total CO2 avoided	Mt	125				
Abatement cost						
Static approach	ú/t	60 360	2 438	1 604	839	-130
Dynamic approach	ú/t	65				

Cost benefit analysis						
with a quicker ramp up	Unit	**2015**	**2020**	**2025**	**2030**	**2050**
Delta purchase and maintenance cost	kú/year	7,6	3,0	1,9	1,2	0,0
Delta fuel cost	kú/year	-0,4	-0,5	-0,3	-0,3	-0,5
Infrastructure for H2	kú/year	13,8	0,3	0,2	0,1	0,1
Delta TCO per vehicle	kú/year	21,1	2,8	1,8	1,0	-0,4
TCO converge in	year	**2041**				
Total discounted delta cost from 2014 to	Mú	20 350	1 897	5 921	11 926	17 104
CO2 emissions avoided	t/year	1,62	1,68	1,35	1,49	1,76
Total CO2 avoided	Mt	170				
Abatement cost						
Static approach	ú/t	13 023	1 662	1 321	667	-211
Dynamic approach	ú/t	48				

For completeness we also provide a sensitivity analysis on the discount rate, using 6% rather than 4%. Table 10 shows that the total discounted cost decreases but that the dynamic abatement cost increases up to 63 €/t (see Appendix 3 for more on the role of the discount rate).

Table 10 The cost benefit analysis with a discount rate at 6 %

Cost benefit analysis						
with 6% discount rate	Unit	**2015**	**2020**	**2025**	**2030**	**2050**
Delta purchase and maintenance cost	kú/year	8,0	3,2	2,0	1,2	0,1
Delta fuel cost	kú/year	-0,4	-0,5	-0,3	-0,3	-0,5
Infrastructure for H2	kú/year	14,4	0,3	0,2	0,2	0,1
Delta TCO per vehicle	kú/year	22,0	3,0	1,9	1,1	-0,3
TCO converge in	year	2043				
Total discounted delta cost from 2014 to	Mú	15 348	1 742	5 120	9 717	13 903
CO2 emissions avoided	t/year	1,62	1,68	1,35	1,49	1,76
Total CO2 avoided	Mt	161				
Abatement cost						
Static approach	ú/t	13 620	1 770	1 417	729	-174
Dynamic approach	ú/t	63				

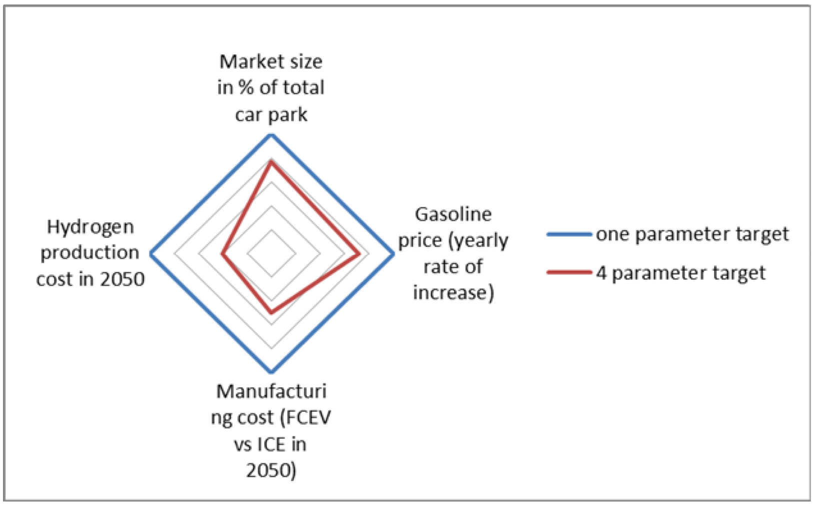
Target analysis

A reasonable estimate for the normative cost of carbon is provided by the Quinet report (2009, 2013). This estimate is around 30€/t for 2015. Another way to make our sensitivity analysis meaningful is to investigate under what conditions our dynamic abatement cost would meet this estimate.

Table 11 gives the simulation results, explicating the change in the key parameters that would be necessary to eliminate the gap. Two cases are considered: one parameter or all four parameters change. It would be interesting to carefully evaluate the empirical credibility of the individual or global changes. The targeted learning rates for manufacturing cost and hydrogen production cost could be put in line with the acceptability of cars by consumers. The all four parameter change illustrates this point

Table 11 Target analysis to get the normative cost of carbon as the abatement cost

Target analysis	unit	base case	one parameter target	4 parameter target
Dynamic abatement cost	ú/t	53	30	30
Market size in % of total car park	%	15%	26%	20%
Gasoline price (yearly rate of increase)	%	1,40%	2,80%	2%
Manufacturing cost (FCEV vs ICE in 2050)	%	12%	8%	10%
Hydrogen production cost in 2050	ú/kg	6,8	4,8	6,0
	%		-30%	-12%



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Suggested research issues

This study provides a consistent set of technological and cost assumptions under which FCEV would be a socially beneficial alternative for decarbonizing 15% of the projected German car park at the horizon 2050. The analysis is using gasoline ICE as the alternative technology. The cost benefit framework used for the study suggests a number of developments to comfort the validity of this conclusion. We briefly discuss the two research issues which we consider as the more relevant.

The study starts from an exogenous deployment for FCEV and infers cost components. It would be preferable to rely on a supply and demand model. This extension would make the deployment for FCEV endogenous and depending on the public and private instruments that could induce the decreasing of costs and the acceptance of the FCEV technology by consumers. The environmental objective could be made endogenous and related to a global objective for the whole transport system and the expected contributions of different power-trains. This is partly done in the previous studies; however these studies do not address the question of the timing of the public and private instruments that would trigger the underlying learning by doing. Should the deployment be accelerated or should it be postponed? How should it be phased over time? This is a recurrent debate for green technologies. We have seen that static abatement costs for FCEV are a crude way to discuss the timing issue and may easily lead to conflicting views. Our formulation of dynamic abatement costs is a first step to a more appropriate economic setting. This first step should be refined and related to the emerging literature on the optimal dynamic deployment of renewable technologies.

The study highlights the complementarity nature of manufacturing FCEV, H2 production and H2 distribution. Under our assumptions this complementarity is particularly severe in the launching period (2015-2020) but also persists over time. Complementarity ordinarily induces inefficiencies due to the so-called hold up problem: The sunk costs necessary for investment cannot be recouped through a market equilibrium based on marginal costs. The economic textbook answer would be to allow integration. More realistically in the context of FCEV the three goods will be provided by different players originating from different industries; an institutional framework specifying contracts among the parties need be designed. These contracts would specify for instance commitments in terms of investments and deployments, conditions for these commitments, revision clauses… The design of a proper institutional framework for cooperation among these industries while preserving competition within each industry is an important research issue for the success of H2 mobility.

Glossary

200/700 bar	Pressure levels for hydrogen storage tanks
AL	Air Liquide Company
BEV	Battery Electric Vehicle
capex	Capital Expenditures
CEP	Clean Energy Partnership
CO2	Carbon Dioxide
FCEV	Fuel Cell Electric Vehicle
g	Gram
H2	Hydrogen
H2M	Hydrogen Mobility project
HRS	Hydrogen Refuelling Stations
ICE	Internal Combustion Engine
k€	Thousands of Euros
kg	Kilogram
km	Kilometer
l	Liter
MJ	Mega joule
OPEX	Operating Expenses
SMR	Steam Methane Reforming
SMR + CCS	Steam Methane Reforming with Carbon Capture and Storage
TCO	Total Cost of Ownership
t	ton
VAT	Value-added tax

Appendix 1: A selected review of the recent literature on the hydrogen mobility

1. Achtnicht, M., G. Bühler and C. Hermeling (2008) '*Impact of service station networks on purchase decisions of alternative-fuel vehicles*', Discussion Paper no. 08-088, Zentrum für Europäische Wirtschaftsforschung

Objective: The paper studies the impact of service station availability on the demand for alternative-fuel vehicles.

Results: The results suggest that a failure to expand the availability of alternative fuel stations represents a significant barrier to the widespread adoption of alternative-fuel vehicles. Considering in addition that hydrogen and electric cars are likely to remain more costly than their conventional counterparts due to expensive fuel cells and batteries, the barriers to widespread adoption are considerable.

Methodology: Analysis is based on stated preference data from a discrete choice experiment carried out in Germany, and considers a broad range of fuel types. Applying a standard logit model, the authors show that fuel availability influences choices positively, but its marginal utility diminishes with supply. Furthermore, consumers' marginal willingness to pay for an expanded service station network is derived.

2. Beeker E. (2014) *'Y a-t-il une place pour l'hydrogène dans la transition énergétique?'*, Note d'analyse, France Stratégie, Commissariat général à la Stratégie et à la Prospective, available at

http://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/201-08-06na-fs-hydrogene-hd.pdf

Objective: The author discusses the role of hydrogen technology in the energy transition in France.

Results: This study revisits how hydrogen technology can contribute to the energy transition. According to the author Fuel cell electric vehicles (FCEV) cannot yet compete with incumbent internal combustion engine (ICE) technology because of high cost of key components, high electrolysis costs and inexistent infrastructure. The author suggests continuing R&D for electrolyzes and fuel cells in order to improve economic and technical performance.

Methodology: The study is based on interviews of industry representatives.[6]

[6] Air Liquide has been interviewed but disagrees with the conclusions of this report.

3. Bruegel Institute – Zachmann G., Holtermann M., Radeke J., Tam M., Huberty M., Naumenko D., and Ndoye A. (2012) '*The great transformation: decarbonising Europe's energy and transport systems*', Bruegel Blueprint Series, Volume XVI, available at

http://www.bruegel.org/publications/publication-detail/publication/691-the-great-transformation-decarbonising-europes-energy-and-transport-systems/

Objective: This study compares the industry scenario (Mc Kinsey, 2010) for the deployment of FCEV to an endogenous scenario depending on the consumers' acceptance for this new technology and conditional on the public policies that could potentially support this deployment. d.

Results: The authors argue that a consistent policy approach is needed. Policy intervention appears indispensable as the existing energy and transport system is locked-in into an incumbent technology. Overcoming this lock-in is crucial. The report makes three main proposals. First, the scope, geographical coverage and duration of carbon pricing should be extended. By setting a higher carbon price, incentives for developing and investing in new low-carbon technologies are created. Second, temporary consortia for new infrastructure to solve early-phase market failures could be put in place. Lastly, an open and public transition model is needed so that transport solutions do not get a head start that afterwards would be reversed.

Methodology: This study analyses possible decarbonisaton strategy of the transport sector in Europe with respect to expected economic, environmental and societal benefits. The second chapter of the study examines existing commercial and policy gaps in the case of fuel cell electric vehicles. At the centre of the gap analysis are two questions: (1) what conditions are needed for fuel cell electric vehicles to become a successful technology and (2) how much of these will the market provide autonomously in the business-as-usual case without policy intervention? To answer those questions the authors use a model based approach. It utilises the Market Model Electric Mobility (MMEM) – a simulation tool developed by the European School of Management and Technology in 2011. MMEM is a simulation model designed to forecast and evaluate policies that aim to promote the diffusion of alternative-fuel vehicles. Its core component is a market simulation module that is based on discrete choice modelling to forecast the evolution of different automotive technologies on the German market. It covers nine competing technologies (gasoline, diesel, hybrid, biofuels, LPG-CNG, battery electric vehicles, range extender, plug-in hybrid, fuel cell).

4. California Environmental Protection Agency – Air Resources Board (2009) '*California exhaust emission standards and test procedures for 2009 and subsequent model zero-emission vehicles and hybrid electric vehicles, in the passenger car, light-duty truck, and medium-duty vehicle classes*', retrieved on 7 October 2011 from

http://www.arb.ca.gov/msprog/levprog/cleandoc/clean_2009_my_hev_tps_12-09.pdf

Objective: This document provides the requirements necessary to complete an application for certification of zero-emission vehicles and hybrid electric (this document is incorporated in California Code of Regulations).

Results: This document describes ZEV emissions standards and imposes the minimum percentage ZEV requirement for each manufacturer as it is listed in the table below:

Model Years	*Minimum ZEV Requirement*
2009 through 2011	11 %
2012 through 2014	12 %
2015 through 2017	14 %
2018 and subsequent	16 %

Moreover, it defines "ZEV fuel" as a fuel that provides traction energy in on-road ZEVs (examples of current technology ZEV fuels include electricity, hydrogen, and compressed air).

Methodology: The emission standards and test procedures in this document are applicable from 2009 and subsequent model-year zero-emission passenger cars, light-duty trucks, and medium-duty vehicles, and 2009 and subsequent model-year hybrid electric passenger cars, light-duty trucks, and medium-duty vehicles.

5. Farrell, A.E., D. W. Keith and J. J. Corbett (2003) *'A strategy for introducing hydrogen into transportation',* Energy Policy 31(13): 1357-1367

Objective: The paper focuses on one aspect of strategy for introducing hydrogen — the choice of transportation mode.

Results: The analysis suggests that cost of introducing hydrogen can be reduced by selecting a mode that uses a small number of relatively large vehicles that are operated by professional crews along a limited number of point-to-point routes or within a small geographic area. In addition, technological innovation in vehicle design will take place most quickly in modes where individual vehicles are produced to order and each receives significant engineering attention (not those manufactured in vast quantities on assembly lines). The immediate environmental benefits of introducing hydrogen fuel will occur in modes that have relatively less stringent pollution regulations applied to them. These insights, suggest that heavy – duty freight modes would be a less costly way to introduce hydrogen as a transportation fuel and a more effective way to advance hydrogen-related technologies so that they could subsequently be used more widely in light-duty vehicles.

Methodology: Comparative review analysis which suggests that the overarching goal of introducing hydrogen as a transportation fuel should be to develop the cluster of technologies and practices associated with its use at minimal public cost and social disruption.

6. HyWays (2008) *'The European hydrogen energy roadmap'*, available at
http://www.hyways.de/

Objective: This study analyses the potential impacts on the EU economy, society and environment of the large-scale introduction of hydrogen in the short- and long- term (up to 2050).

Results: Firstly, the HyWays "Roadmap" shows that hydrogen can become a cost-effective option for the reduction of CO_2 in the long-term (total well-to-wheel reduction of CO_2 emissions will amount to 190 – 410 Mton per year in 2050 for the 10 countries analysed in HyWays). Secondly, it indicates that hydrogen introduction may lead to a substantial improvement in the security of energy supply (the total oil consumption of road transport could be decreased by around 40% by the year 2050 as compared to today if 80% of the conventional vehicles were replaced by hydrogen vehicles). Thirdly, the project highlights that hydrogen, if produced through sustainable pathways, offers the opportunity to increase the utilisation of renewable energy in Europe (hydrogen could also act as a temporary energy storage option and might thus facilitate the large-scale introduction of intermittent resources such as wind energy).

Methodology: The HyWays project compiles technological and socio-economic aspects related to a future hydrogen infrastructure build-up. The penetration rate is exogenously given only based on the cost-effectiveness of the hydrogen technology. It shows the consequences of the introduction of hydrogen as a fuel and indicates the financial effort necessary to reach the break-even point. The qualitative data from stakeholders is incorporated with quantitative infrastructure analysis, thus adding significantly to the common quantitative modelling approach adopted by other roadmaps. In the HyWays project the Roadmap is based primarily on country-specific analyses of ten member states (Finland, France, Germany, Greece, Italy, the Netherlands, Norway, Poland, Spain and the United Kingdom).

7. McKinsey & Company (2010) *'A portfolio of power-trains for Europe: a fact-based analysis. The role of battery electric vehicles, plug-in hybrids and fuel cell electric vehicles*, available at
http://www.iphe.net/docs/Resources/Power_trains_for_Europe.pdf

Objective: This study on passenger cars compares alternative power-trains most likely to fulfil the EU CO2 reduction goal for 2050. Subsequently, it re-assesses the role of FCEVs in the light of recent technological breakthroughs in fuel cell and electric systems that have increased their efficiency and cost-competitiveness significantly.

Results: Firstly, BEVs, PHEVs and FCEVs have the potential to significantly reduce CO2 and local emissions, assuming CO2 reduction is performed at the production site. Secondly, all electric vehicles are viable alternatives to ICEs by 2025, with BEVs suited to smaller cars and shorter trips, FCEVs for medium/larger cars and longer trips. With tax incentives, BEVs and FCEVs could be cost-competitive with ICEs as early as 2020. Thirdly, costs for a hydrogen infrastructure are approximately 5% of the overall cost of FCEVs (€1,000-2,000 per car) and comparable to rolling out a charging infrastructure for BEVs and PHEVs. Finally, the deployment of FCEVs will incur a cost to society in the early years because it requires close value chain synchronisation and external stimulus in order to overcome the first-mover risk of building hydrogen retail infrastructure.

Methodology: A factual evaluation of BEVs, FCEVs, PHEVs and ICEs based on proprietary industry data. A combined forecasting and backcasting approach was used to calculate the results: from 2010 to 2020, global cost and performance data were forecasted based on proprietary industry data; after 2020, on projected learning rates. The conclusions are showed to be robust to significant variations in learning rates for the power-trains and the cost of fossil fuels.

8. Mui, S. and A. Baum (2010) *'The zero emission vehicle program: an analysis of industry's ability to meet the standards'*, Natural Resources Defense Council, available at
http://docs.nrdc.org/energy/files/ene_10070701a.pdf

Objective: Since the 1990s, California's Zero Emission Vehicle (ZEV) program has served as a critical technology-forcing component of the state's vehicle emissions program. The goals of the ZEV program include helping assure the transformation needed for very low or zero-emitting vehicles consistent with the State goal of an 80% reduction in GHG emissions by 2050. An assessment was conducted to evaluate automaker's ability to comply with the ZEV requirements in California and in other states that have adopted the standards.

Results: The results of the forecasts show that the U.S. market for electric-drive vehicles will grow from approximately 85,000 vehicles in model year (MY) 2012 to between 320,000 to 540,000 by MY 2015, with cumulative U.S. sales reaching 1 to 1.3 million for electric-drive vehicles by 2015. The range reflects low and high oil price cases. Slightly over one-quarter of these vehicles are estimated to be produced by new entrants. Overall, the forecasts show that the auto industry will likely over-comply with the ZEV requirements through the MY 2020 time period even for a low-growth case scenario that holds MY 2015 sales nearly flat out to MY 2020.

Methodology: Forecasts generated by The Planning Edge were conducted on automakers' planned production and sales of electric-drive vehicles over the next five model years. Over forty vehicle models from twelve major original equipment manufacturers (OEMs) and ten new entrants are considered in the forecasts.

9. NREL (2007) *'Validation of hydrogen fuel cell vehicle and infrastructure technology'*, National Renewable Energy Laboratory, available at
http://www.nrel.gov/hydrogen/pdfs/42284.pdf

Objective: The U.S. Department of Energy (DOE) has a major program for research and development of hydrogen and fuel cell technology. A key element of that research and development is the five-year, $175-million industry-cost-shared "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project."

Results: Key DOE targets for the program for 2009 at the end of the initial validation project, and for 2015 to meet objectives believed adequate for consumer acceptance include: 5,000 hours is equivalent to about 161,000 km (100,000 miles) for an average vehicle. Other important parameters that the validation project is tracking include refueling time, dynamometer and on-road fuel economy, cold-weather starting, safety incidents, fuel impurities, and storage tank capacity per volume and weight.

Methodology: Through a 2003 competitive solicitation, DOE selected four automobile manufacturer/energy company teams to participate in the project— Chevron/Hyundai-Kia, DaimlerChrysler/BP, Ford/BP, and GM/Shell. DOE is cost-share funding those teams to build small fleets of fuel-cell vehicles plus fueling stations to demonstrate their use in five regions in the United States. DOE's National Renewable Energy Laboratory (NREL) has set up a data-collection and analysis system with the teams for the project. The system collects extensive data on the demonstration fleets and infrastructure. NREL researchers use the data to validate progress toward meeting DOE objectives for hydrogen and fuel cell technology and help guide future research and development. NREL validation project provides multiple outputs to different stakeholders. Aggregated general results are reported publicly as "composite data products."

10. Roads2HyCom (2009) '*Fuel cells and hydrogen in a sustainable energy economy'* – final report of the ROADS2HYCOM project, available at

http://www.roads2hy.com/r2h_downloads/Roads2HyCom%20R2H8500PUv6%20-%20Final%20Report.pdf

Objective: The objective of Roads2HyCom is to assess and monitor current and future Hydrogen and Fuel Cell technologies for stationary and mobile energy generation for current and future application requirements, and the needs of communities which may adopt these technologies, in order to support the Commission and stakeholders in planning future activities.

Results: Firstly, the technological state of the art is advancing significantly, but the right support and incentives are required to address critical issues and realise recent progress in volume-produced applications; as well as developing the engineering, manufacturing and servicing skill-base to support their arrival in the market. Secondly, there are significant early markets created by specialised application niches and by the political will of municipal early adopters; these markets need to be encouraged and replicated by implementing appropriate policy, in a manner that is stable long-term, at European level. Thirdly, there is a critical need to link the development of sustainable and low carbon energy policy, to that for the supply of Hydrogen as a fuel, so that the environmental potential of hydrogen-fuelled applications can be fully realised. The linkage to grid development and sustainable electricity (which both complements and competes with hydrogen as an energy vector) is especially critical.

Methodology: The project has studied (through a framework of metrics) technical and socio-economic issues associated with the use of Fuel Cells and Hydrogen in a sustainable energy economy, by combining expert studies in technology status, energy supply and socio-economics with an active programme of engagement with key stakeholders, especially early adopters of the technologies.

11. Schoots, K., G. Kramer and B. van der Zwaan (2010) *'Technology learning for fuel cells: an assessment of past and potential cost reductions'*, Energy Policy vol. 38(6): 2887-2897

Objective: Fuel cells have gained considerable interest as a means to efficiently convert the energy stored in gases like hydrogen and methane into electricity. This study characterizes cost, safety and reliability levels necessary to achieve widespread use in the energy transition.

Results: The authors estimate the current cost of fuel cell at about 1100€ (2005)/kW for an 80 kW fuel cell systems but note that specific costs vary markedly with fuel cell system power capacity. For PEMFC technology they calculate a global learning curve, characterized by a learning rate of 21% with an error margin of 4%. Given their respective uncertainties, this global learning rate value is in agreement with those the authors find for different manufacturers. In contrast to some other new energy technologies, R&D still plays a major role in today's fuel cell improvement process and hence probably explains a substantial part of the observed cost reductions. The remaining share of these cost reductions derives from learning-by-doing proper. Since learning-by-doing usually involves a learning rate of typically 20%, the residual value for pure learning for fuel cells is found to be relatively low. In an ideal scenario for fuel cell technology the authors estimate a bottom-line for specific (80kWsystem) manufacturing costs of 95€ (2005)/kW.

Methodology: The study analyzes past fuel cell cost reductions for both individual manufacturers and the global market. The authors determine learning curves, with fairly high uncertainty ranges, for three different types of fuel cell technology – AFC, PAFC and PEMFC – each manufactured by a different producer.

12. The Connecticut Center for Advanced Technology Inc. (2011) *'Connecticut Hydrogen and Fuel Cell Deployment Transportation Strategy',* available at

http://www.chfcc.org/Publications/reports/CT%20Hydrogen%20Trans%20Strategy1-13-10%20Final%20Plan.pdf

Objective: This strategic Plan provides information and directions for the deployment of hydrogen and fuel cell technology to support transportation in the state of Connecticut.

Results: Market: the U.S. Department of Energy has projected that between 15.1 million and 23.9 million light duty fuel cell vehicles will be sold each year by 2050 and between 144 million and 347 million light duty fuel cell vehicles will be in use by 2050 with a transition to a hydrogen economy. These government estimates could be accelerated if political, economic, energy security or environmental polices prompt a rapid advancement in alternative fuels. Environmental performance: the use of fuel cells, and especially fuel cells that directly utilize hydrogen, provides high value for improving air quality and reducing greenhouse gas (GHG) emissions. It has been calculated that the potential annual emissions reductions are between 26.2 and 37.3 pounds of NOx; 0.192 and 0.299 pounds of SO2; and 10,169 and 15,772 pounds of CO2 per passenger vehicle and light duty truck, respectively. For each transit bus, the potential emissions reductions have been calculated at approximately 1,020 pounds of NOx; 1.75 pounds of SO2; and 183,000 pounds of CO2 annually.

Deployment: Connecticut is expected to have four hydrogen refueling stations in operation by 2011. With support from the federal and state government and private industry, approximately seven or eight hydrogen refueling stations could be in operation by 2020, and as the market expands this could result in over 1,000 hydrogen refueling stations in operation by 2050. In summary, information in this plan suggests that a transition to a hydrogen economy and the deployment of zero-emission, hydrogen fuel cell buses state-wide will increase transportation efficiency, improve environmental performance, increase economic development, and create new jobs.

The technical and financial arrangements needed for such a transition from conventional vehicles and bus fleets will require initial investment by the state and federal government and private industry; however, such investment is well justified and will become a necessity as concerns about public health and climate change increase and the supply of conventional fuels becomes more limited.

Methodology: The Department of Transportation in collaboration with the Connecticut Center for Advanced Technology, Inc. develops a plan to implement zero-emissions buses state-wide. This plan includes the technological, facility and financial arrangements needed for such a conversion of bus fleets as well as identifying specific locations for hydrogen refueling stations along state highways or at locations that could potentially be utilized by state fleets or other public or private-sector fleets. This is a part of a larger collaborative effort between the Department of Transportation and the Connecticut Center for Advanced Technology, Inc. to identify strategies to expand the availability and use of hydrogen fuel and renewable energy sources within any such corridor or around such a centralized fleet fueling location. The plan is completed within available appropriated funds designated for the purpose of studying or designing clean fuel or alternative fuel solutions.

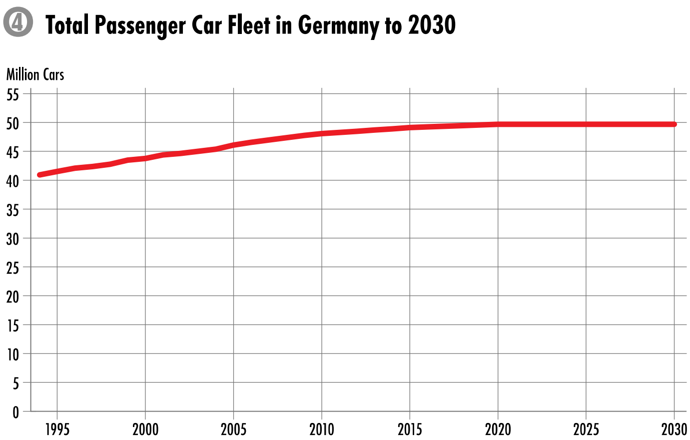
Appendix 2 Data and Sources

Market size

The total passenger car fleet in Germany is assumed to increase from today's level of 47 million vehicles to 49.5 million in 2030 (Shell, 2009). The car park is assumed to be stable from 2030 to 2050. We assume a target in 2050 for the FCEV car park at 15% of the total car park that is, 7.500 million units. This defines the base scenario. We introduce two variants:

- A slower ramp-up scenario in which the target is reduced to 12%;
- A quicker ramp-up scenario in which the target is increased to 20%;.

Figure 2.1 Total passenger car fleet in Germany



Our 15% assumption for the H2 car park can be put in the following perspective: Assumptions on the vehicle mix in 2035 in Germany depend on the power-train scenarios: No Change, Diesel Dominates, and Alternative Technologies Emerge. For example, in the study of Kristian Bodek & John Heywood (2008) Gasoline ICE represents 52%, 20%, and 15% of the total mix respectively.

We assume that the average life time of a car is 10 years and that it runs approximately 15 000 km per year (The Economist, 2012).

Manufacturing costs

FCEV and ICE purchase prices for the base scenario are based on *A portfolio of power-trains for Europe: a fact-based analysis* forecast (Mc Kinsey & Company, 2010). The data is available for 2020, 2030 and 2050 for B/C car segment. We assume data value in 2015 be the same as 2014 averaged market value. The data for interim years is obtained by linear extrapolation of available data for ICE and on a leaning rate for FCEV.

Yearly FCEV and ICE maintenance costs are assumed to be a constant percentage of the purchase costs, equal respectively to 8% and 10 %. These values are constant during all time period studied in the model. The lower value for *FCEV maintenance cost* comes for instance from less rotating mechanism in the power train.

For sensitivity analysis we assume *FCEV purchase* price varying according to learning-by-doing effect with respect to the following formula:

$$P_n=P_1*(N_1/N_n)^{\mu},$$

where P_n is FCEV price in the year *n*; P_1 is FCEV price in 2015; N_n is a cumulated number of FCEVs constructed up to *n* year; N_1 is a cumulated number of FCEVs constructed in 2015; and μ is learning rate. The *FCEV purchase price base scenario* corresponds to the learning rate calibrated at is -0,1 which gives a FCEV purchase price 13% higher than the ICE purchase price in 2050. The calibration is made to fit the raw data of market deployment with associated manufacturing cost over time. The *high learning rate scenario* corresponds to a learning rate of -0,113, for which FCEV and ICE have identical purchase prices in 2050.

Table 2.2 ICE and FCEV manufacturing and maintenance costs scenarios

Manufacturing costs	**2015**	**2020**	**2030**	**2050**
ICE purchase price base scenario (k€)	22	21,4	21,1	20,5
ICE maintenance cost	10%	10%	10%	10%
FCEV purchase price calibration set (k€)	60	30,9	25,7	23,7
1. FCEV purchase price base scenario (k€) learning rate = .10	60	37,9	28,9	23,1
2. FCEV purchase price with learning rate = .11 (k€)	60	35,7	26,3	20,5
3. FCEV purchase price with learning rate = .12 (k€)	60	34,6	24,9	19,1
FCEV maintenance cost	8%	8%	8%	8%

Fuel costs for hydrogen

Hydrogen consumption The data for 2015, 2020, and 2030 is based on AL estimates. The data for interim years is obtained by linear extrapolation of available data.

Table 2.3 Hydrogen energy efficiency

Hydrogen consumption	**2015**	**2020**	**2030**	**2050**
kg H2/ 100km	0,95	0,87	0,80	0,7

Hydrogen can be produced via different technologies: steam methane reforming using natural gas (SMR), SMR with carbon capture and storage (SMR + CCS), SMR with biogas, and electrolysis.

The individual cost of production for the different technologies is based on internal AL data.

-*SMR + Natural gas*,

The hydrogen production cost due to SMR technology is composed of two types of cost, which contribute to final hydrogen production cost: first, the fixed cost, which is related to investment in specific production capacity (assumed to be constant over time; no inflation taken into account); second, the variable cost due to the natural gas price evaluation (assumed to follow the same trend as the oil price). The initial data is available for 2015.

-*SMR + CCS*

As a simplified approach, the hydrogen production cost due to SMR+CCS technology is supposed to be 25% more expensive than SMR.

-*Electrolysis*

The hydrogen production cost due to electrolysis technology is calculated with respect to learning-by-doing effect. The initial data is available for 2015. The introduced learning rate of -0,042 based on the cumulative hydrogen production is calculated to fit industry forecast.

-*SMR + Biogas*

The hydrogen production cost due to biogas and SMR technologies is calculated with respect to learning-by-doing effect and takes into account cumulative hydrogen production. The initial data is available for 2015. The learning rate for the cost reduction is calibrated according to the industry forecast and is equal to -0,010.

Table 2.4 Hydrogen production cost for different production technologies

H2 production cost for individual techno		2015	2020	2030	2050
SMR +natural gas	ú/kg	2,9	2,9	3,0	3,3
SMR + CCS	ú/kg	3,6	3,6	3,8	4,1
Electrolysis	ú/kg	8,0	6,0	5,0	4,4
SMR + Biogas	ú/kg	6,0	4,9	4,3	4,0
Logistic cost (delivery to HRS)	ú/kg	4,0	2,1	2,2	2,6

A logistic cost supposes delivery to the HRS by 200 bar tube trailers and is to be added to all production costs. The decrease in cost is mainly due to a higher density of H2 sources and HRS network, reducing distances to cover. The decrease could even be more important if we take into account technological breakthroughs like the 700 bar logistic.

From these pure production scenarios, which suppose only one production technology, several mixed scenarios can be constructed in which a respective dominant technology is progressively introduced.

Table 2.5 Contribution of different technologies to the hydrogen production mix scenarios

Selected mix	**2015**	**2020**	**2030**	**2050**
Base scenario				
SMR + natural gas	96%	65%	35%	5%
SMR + CCS	0%	5%	5%	30%
Electrolysis	2%	15%	35%	40%
SMR + Biogas	2%	15%	25%	25%
SMR scenario				
SMR	100%	100%	100%	100%
SMR+CCS scenario				
SMR + natural gas	96%	85%	20%	10%
SMR + CCS	0%	5%	50%	60%
Electrolysis	2%	5%	10%	10%
SMR + Biogas	2%	5%	20%	20%
Electrolysis scenario				
SMR + natural gas	96%	78%	30%	5%
SMR + CCS	0%	2%	5%	5%
Electrolysis	2%	15%	60%	85%

SMR + Biogas	2%	5%	5%	5%
Biogas scenario				
SMR + natural gas	96%	78%	30%	5%
SMR + CCS	0%	2%	5%	5%
Electrolysis	2%	5%	5%	5%
SMR + Biogas	2%	15%	60%	85%

The cost of hydrogen production for each of these scenarios is then calculated as the weighted average of costs of respective technologies contributing to the selected mix.

Discussion of H2 production scenarios

Different hydrogen production technologies have certain technological and economic constraints. This section briefly presents them.

-*SMR +Natural Gas*

SMR is a well mastered and widely used technology that implies low cost (2,86 €/kg of hydrogen) but CO2 emissions remain substantial (8,69 kg of CO2 emitted for 1 kg of hydrogen produced; or 9,78 kg of CO2 for 1 kg of hydrogen produced and delivered to the HRS; according to JRC, 2014 p. 135) still 20% less CO2 from well to wheel than an ICE. This technology does not represent the best solution for the drastic CO2 carbon reduction targeted in transport but could serve as a good base of comparison for other hydrogen production technologies, which are more environmentally friendly.

- *SMR+CCS*

SMR+CCS technology relies on a similar technical process as SMR. CCS allows capturing 84% of carbon emissions compare to SMR (JRC, 2013) but implies around 25% increase in production cost. However, SMR+CCS technology faces difficulties in social acceptance. Moreover, the cost of carbon storage depends a lot on the localisation of storage (saline cave). The saline cave should be next to the place of hydrogen production; otherwise the high transportation cost of CO2 drives up hydrogen production cost. The limited availability of saline caves in certain areas represents therefore a physical constraint for hydrogen production via SMR+CCS technology.

- *Electrolysis*

The electrolysis technology of hydrogen production is carbon free if renewable electricity is used (the only carbon emissions are related to the transportation of hydrogen to the HRS). However, it is currently relatively costly (8 €/kg of hydrogen). The main contributors to the hydrogen cost produced via electrolysis are the equipment cost and the electricity price. In order to bring down the equipment cost, the industrial actors target 35-50% capex electrolyser reduction on top of technological improvement for fast frequency change in electrolyser adaptability. This fast frequency change regime will allow consuming cheap electricity in addition to equilibrating electricity network, and therefore will drive down the electricity price component. These measures allows in the long term to achieve a targeted 4.5 €/kg price for hydrogen produced via electrolysis technology in spite of increase in the average electricity price.

- *SMR + Biogas*

Biogas technology of hydrogen production relies on a similar technical process as SMR. The current cost is relatively high (6,00 €/kg of hydrogen). This cost is mainly composed of equipment depreciation cost (about 1-2 €/kg of hydrogen) and of bio-methane cost (about 3-4 €/kg of hydrogen). The cost of hydrogen produced via biogas can be brought down for example if the cost of biogas is reduced. Nowadays, the bio-methane price is regulated and differs from one country to the other. New technologies of SMR are also studied to reduce the need for purification of the biogas used in the process.

Fuel costs for ICE

Gasoline consumption relies on IEA (2013) data projection up to 2040. We assume engine energy efficiency to remain unchanged from 2040 to 2050.

Gasoline price per litre scenarios are based on IEA (2013) crude oil price projections. The data are available up to 2040. From these projections we infer a yearly long term growth rate at 1.4 % in real terms (without VAT and TIPP). We introduce various scenarios corresponding to various annual growth rates: 4% for a high oil price and 0% for a low oil price. The average gasoline market price per litre in Germany in March 2014 was equal to 1,6 € (including all taxes). In our calculation we exclude the German 19% VAT tax on gasoline. We estimate another state tax in Germany (equivalent to the French TIPP) in 2014 at .65 €/l (sources http://energytransition.de/2012/10/environmental-taxation/ and IEA statistics Energy prices and taxes, 2014 Q2); this (volume) tax is included in our analysis since it represents an opportunity cost for importing oil. It is assumed to be constant over the time period 2015-2050. Gasoline prices in Germany without taxes are supposed to follow the same variation as for crude oil world prices.

Table 2.6 Gasoline consumption and market prices (TVA excluded TIPP included) scenarios

Gasoline consumption per 100 km:		annual growth rate	**2015**	**2025**	**2030**	**2050**
Gasoline consumption EIA scenario	l/100 km		7,04	4,97	4,88	4,80
1. Gasoline price reference scenario	ú/l	1,4%	0,65	0,75	0,80	1,06
2. Gasoline price high scenario	ú/l	4,0%	0,72	1,07	1,30	2,85
3. Gasoline price low scenario	ú/l	0,0%	0,64	0,64	0,64	0,64

Hydrogen infrastructure cost

HRSs are supposed to have 10 years lifetime up to 2020 included, and 15 years lifetime afterwards. The total number of HRSs is derived from the hydrogen consumption, the mix of HRSs and their respective capacities. The total HRS park generates capital and operating expenses. An initial *HRS base coverage* is predefined in the model for years 2015-2017.[7] HRS capacity is different from nominal HRS capacity. It takes into account the fact that HRSs are delivering hydrogen only 17 and not 24 hours per day.

[7] Air Liquide, 2014, Press Kit, "Hydrogen, a clean Energy", available at http://www.airliquide.com/file/otherelement/pj/5a/3d/a8/d0/air-liquide-hydrogen-energy-press-kit-2014-3687827655611538647.pdf

Assumptions for HRS production and maintenance costs are based on AL data. They correspond to industry estimates and a learning rate of -.06. Variants are introduced for this learning rate: -.1 and -.02 for a high respectively low learning rate.

Table 2.7 HRS mix, cost and capacity assumptions

HRS scenarios					
Mix for new HRS:		**2015**	**2020**	**2030**	**2050**
HRS 80 kg/d	%	10%	10%	0%	0%
HRS 200 kg/d	%	80%	80%	50%	50%
HRS 400 kg/d	%	10%	10%	30%	30%
HRS 1000 kg/d	%	0%	0%	20%	20%
1. HRS cost base case:		**2015**	**2020**	**2030**	**2050**
HRS 80 kg/d cost base case	kú	1500	1000	872	783
HRS 200 kg/d cost base case	kú	1500	1000	872	783
HRS 400 kg/d cost base case	kú	2000	1732	1418	1235
HRS 1000 kg/d cost base case	kú	3000	3000	2301	1984
2. HRS cost within high learning rate scenario:		**2015**	**2020**	**2030**	**2050**
HRS 80 kg/d cost within high learning rate	kú	1500	879	699	585
HRS 200 kg/d cost within high learning rate	kú	1500	879	699	585
HRS 400 kg/d cost within high learning rate	kú	2000	1574	1128	895
HRS 1000 kg/d cost within high learning rate	kú	3000	3000	1928	1506
3. HRS cost within low learning rate scenario:		**2015**	**2020**	**2030**	**2050**
HRS 80 kg/d cost within low learning rate	kú	1500	1348	1288	1243
HRS 200 kg/d cost within low learning rate	kú	1500	1348	1288	1243
HRS 400 kg/d cost within low learning rate	kú	2000	1906	1784	1703
HRS 1000 kg/d cost within low learning rate	kú	3000	3000	2746	2614
HRS OPEX/CAPEX ratio	%	10%	8%	8%	8%
Retained HRS capacity:					
HRS 80 kg/d	kg/d	60			
HRS 200 kg/d	kg/d	170			
HRS 400 kg/d	kg/d	340			
HRS 1000 kg/d	kg/d	700			

CO2 emissions

The *CO2 gasoline emissions* are 87.8 gCO2/MJ (JRC, 2013). The energy content of one litre of gasoline is 32 MJ.

CO2 hydrogen emissions data is available in gCO2 per MJ of final fuel for all types of hydrogen production technologies: SMR is 72,4 gCO2/MJ (JRC, 2013), SMR+CSS is 11,9 gCO2/MJ (JRC, 2013), biogas is 17,3 gCO2/MJ (based on municipal waste biogas JRC, 2011). We suppose hydrogen production via electrolysis to be carbon free. The energy content of one kilogramme of hydrogen is 120 MJ.

The CO2 emissions related to the (pipeline or road) transport to market are estimated at 9,1 gCO2/MJ (1,09 kg CO2 / kg H2) and are to be added to the emissions resulting from hydrogen production (JRC, 2014, p.129).

The total CO_2 emissions of hydrogen production scenarios are calculated as the weighted average of CO_2 emissions of respective production technology contributing to the mix.

Table 2.8 CO_2 emissions related to different hydrogen production technologies (excluding delivery to HRS)

CO2 hydrogen emissions by technology	**g CO2 / MJ**	**kg CO2 / kg H2**
SMR	72.4	8,69
SMR + CCS	11.9	1,43
Electrolysis	0	0
Biogas	17,3	2,06

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Appendix 3 Methodology

Standard framework for a cost benefit analysis

The cost-benefit analysis (CBA) is grounded in standard economic theory and is used in most evaluation of public policies related to climate change (for instance Stern, 2006). The objective of a CBA is to determine whether a project (or a policy) increases social welfare and should be implemented. Social welfare is the sum of individual utilities.

Benefits and costs are computed in monetary units; the monetary evaluation requires that all goods (or bads) produced by the project should be properly priced. In our case, a price for CO2 emissions is needed to assess whether hydrogen vehicle should be launched. Our aim is to determine a threshold price at which the project is launched if and only if the price of CO2 is above this threshold. This threshold price could also be interpreted as the *marginal abatement cost* of this technological option; it should also allow the regulator to rank this option among other abatement options (e.g. CCS, renewables, retrofitting).

In order to assess the value of a project, a baseline or "business as usual" scenario, describing what happens if the project is not implemented, is required. In our case we consider that ICE vehicles will progressively be replaced by FCEV vehicles.

For a long-lasting project, two crucial aspects should be stressed. First, benefits and costs at different dates should be aggregated. To do so a discount factor δ is used, which gives the present value of 1€ obtained next year, $\delta=1/(1+r)$, where r is the “discount rate”. Let us denote B_t and costs C_t the total benefits and costs at date t, the net present value (NPV) is the sum of the discounted differences between benefits and costs, which is indeed equal to the difference of the sum of discounted benefits and costs:

$$NPV=\sum_t \delta^t (B_t - C_t) = \sum_t \delta^t B_t - \sum_t \delta^t C_t$$

The project should be launched if the NPV is positive.

Second, to evaluate a project that reduces emissions at different time periods a CO2 price per period is needed. The aim of the analysis is to obtain a CO2 price that represents the abatement cost associated to a deployment trajectory of the FCEV. One difficulty is to obtain a single indicator for a dynamic investment schedule in a long-lasting infrastructure. To do so, we use the methodology of levelized costs.

Social discount rate

There are vivid debates over the proper social rate of discounting (see Dasgupta, 2008 for a clear presentation of the debate). In a well-functioning economy the relevant social discount rate should be equal to the risk-free long-term market interest rate. This leads some authors to choose a discount rate of 4% which corresponds to the average rate of return to US government bonds over the past 200 years (e.g. Newell and Pizer 2003).

Normative cost of carbon

In the following, we refer to the analysis developed by the Quinet Committee (Quinet, 2009), as well as to a recent revision of this report (Quinet, 2013). These reports study the social cost of carbon in the perspective of a cost efficiency analysis, that is, they compute the carbon price trajectory that minimizes the cost to attain a given abatement objective. The objective refers to the constraints as defined for France in the Loi Grenelle de l'Environnement.

Based on theoretical work and validation by large scale models (Poles, Gemini E3, Imaclim R), different estimates of such a value have been released, then compared with international benchmarks, as the table below shows.

Synthèse des valeurs du carbone élaborées par les institutions officielles (en euros 2008)

	France (Boiteux II)	Royaume-Uni (DEFRA)	Union européenne (a)	États-Unis (b)		
				IGSM	MERGE	MiniCAM
2010	32	40 (27,6 £)		nd	nd	nd
2020	43	49 (33,6 £)	40 [17-70]	54	23	20
2030	58	60 (40,9 £)	55 [22 70]	81	40	36
2050	104	88 (60,8 £)	85 [20 180]	177	120	98
Objectif ppme	Nc	450-550	450	550* (c)	550*	550*
Taux actualisation	8 %	3,5 %	4 %	(3-7 %) (d)		
Croissance de la valeur carbone	3 %	2 %	2,5 % (e)	4 % (f)	5,7 %	5,4 %

(a) *Handbook on Estimation of External Cost in Transport Sector* (produced within the study : Internalisation Measures and Policies for all External Costs of Transport, IMPACT, DELFT, décembre 2007.

Source : Centre d'analyse stratégique

(b) Les valeurs données en dollars sont considérées ici comme des valeurs 2008 (le rapport a été publié en juillet 2007) ; on considère par ailleurs un taux de change compatible de 1,3 (sur la période 2004-2007, il a oscillé entre 1,2 et 1,3).
(c) 450 ppme, CO_2 seul.
(d) Le rapport Lebègue rappelle en 2005 qu'on trouve plusieurs références : le General Accounting Office indique que le taux retenu doit être égal à celui des obligations du Trésor, dont la maturité correspond à la durée des projets évalués. En 2005, ces taux étaient compris entre 3,5 % et 4 %.
(e) et (f) Taux de croissance annuels recalculés sur la base des valeurs affichées en 2020 et 2050.

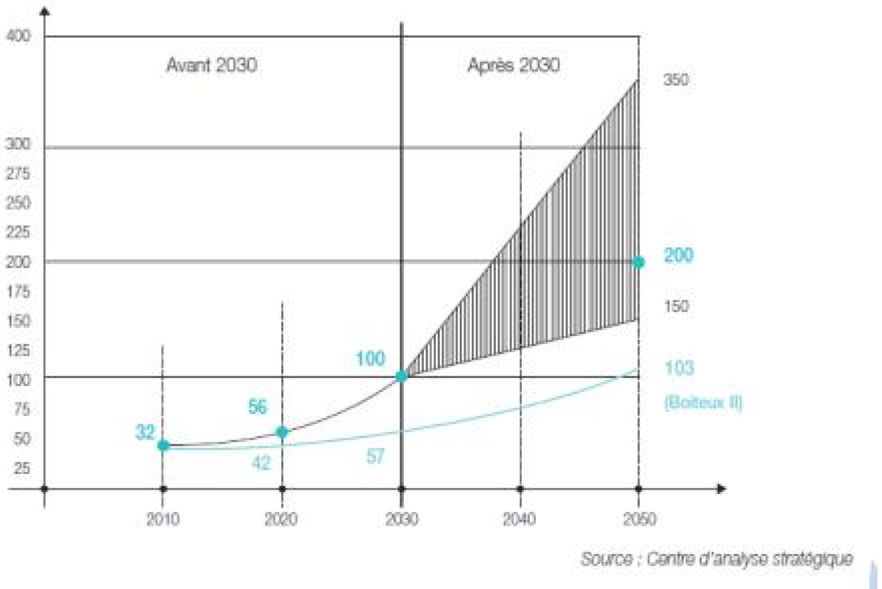
Source : Centre d'analyse stratégique, rapport A. Quinet

In all cases, the carbon price increases through time (with a rate between 2% and 5%). The relationship between the growth rate of the carbon price and the discount rate depends on the policy objective (or the shape of the environmental damage function). The complex optimal dynamics of the carbon price is due to the persistence of GES emissions in the atmosphere.[8]

[8] For instance, if the objective is to stabilize GHG concentration the growth rate of the carbon price should be equal to the discount rate plus the removal rate before the objective concentration is reached (latter emissions

Our base case follows these proposals, namely a 4% discount rate and a CO_2 price growing at 4%.

Normative Cost of Carbon according to the Quinet Committee



Levelized costs

To compute abatement cost from irreversible investment it is common to use levelized costs. This methodology has been intensively used in the electricity industry to compare the production cost of various technologies with different cost structure (fixed/variable cost), life span, and construction delay.

The levelized cost of a technology is the sum of an annualized investment cost and a variable cost. Let's consider the cost of a given technology to produce electricity. The investment cost I in a unit of production capacity (e.g. €/MW) with a life span of N years is transformed into an equivalent annual cost F by the formula :

$$I = F + \delta F + \ldots \delta^{n-1} F = F\,(1 - \delta^{n})/(1 - \delta)$$

So that

$$F = I\,(1-\delta)/(1 - \delta^{n})\,;$$

contribute more to bind the concentration constraint because of the removal rate, and should then be more expensive than earlier emissions, once discounted). The carbon price proposed by the Quinet Committee follows an increasing path, reaching the pivot value of 100 euros in 2030. After this date, an array of values has been proposed, mainly according to the application of the Hotelling rule (that is a CO_2 price growing at the same pace as the discount rate), and different hypotheses on the CO_2 absorption rate and uncertainty.

and adding the yearly fixed and variable (including fuel) operating and maintenance costs *f*:

$$LC=F+f$$

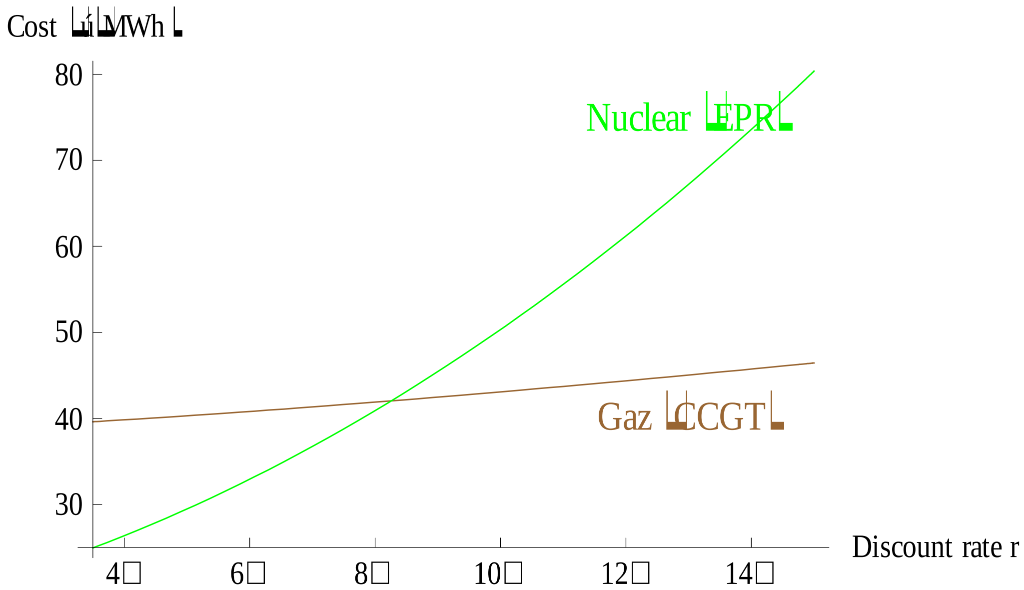
For example, assume that the investment cost of a Combined Cycle Gas Turbine (CCG) is I=500 €/kW, the construction delay is 2 years. The investment cost computed at the date where production starts is $I=500/\delta^2$, the life span is 30 years, the annualized investment cost is $500(1-\delta)/[\delta^2 (1-\delta^{30})]$, for r=8% it gives F=48€/kW/yr. The fixed O&M is 12€/kW, the variable one is 35€/MWh (of which 30 for fuel), so that for a baseload production for a turbine operational 8700 hours per year, the levelized cost for producing 1 MWh is

$$LC= (48+12)/8.7+35=42€/MWh$$

The levelized cost depends on several hypotheses on the technology characteristics:

- If the *utilization factor* decreases, then the levelized cost increases. In our example, if the turbine runs only 3000 hours per year, the cost becomes LC= (48+12)/3+35=56€/MWh.
- The impact of the *discount rate* is illustrated in the Figure below, in which the production cost of nuclear and CCGT are depicted. The cost of each technology is increasing with respect to the discount rate because the opportunity cost of capital increases with the interest rate. The influence of the discount rate is larger for technology with a larger share of investment costs (e.g. Nuclear).[9]

Production cost of Nuclear (EPR) and Gaz (CCGT) as a function of the discount rate



[9] For Nuclear the figures are: the investment cost is 2300€/kW, the construction delay is 5 years, the life span is 50 years, the fixed O&M is 50€/kW and the variable cost (mostly combustible) is 5€/MWh. The figures correspond to DGEMP (2003) except for the investment cost that is larger.

Levelized costs are relevant to compare technologies if several assumptions are satisfied. Typically one considers that the underlying demand to be satisfied is constant, or smoothly growing over time, that the costs of the technologies to be compared are stable over time and that the two technologies are able to produce similar production schedules.

Using levelized cost whenever these assumptions are not satisfied requires some caution. For instance, in the electricity industry, there is a cost associated to renewables intermittency that is not captured by levelized costs.

When relaxing the hypothesis of a discrete production, the previous analysis can be generalized. Consider a production flow q_t for t from 0 to +∞, with $q_{t+1} \geq q_t$:

- first, q_0 plants are built for a cost Iq_0 and produce for a yearly cost fq_0, and N years later the plants should be rebuilt and so on:

$$
\begin{aligned}
C(q_0) &= \left\lfloor Iq_0 + \sum_{t=0}^{N-1} \delta^t fq_0 \right\rfloor + \left\lfloor \delta^N Iq_0 + \sum_{t=N}^{2N-1} \delta^t fq_0 \right\rfloor + ... \\
&= \sum_{t=0}^{N-1} \delta^t (F+f) q_0 + \delta^N \sum_{t=0}^{N-1} \delta^t (F+f) q_0 + ... \\
&= LCq_0 \sum_{t=0}^{+\infty} \delta^t = LCq_0 \frac{1}{1-\delta}
\end{aligned}
$$

- then, at each date the same strategy should be implemented for a marginal increase in production of q_{t+1}-q_t . The total cost to produce the flow is simply the levelized cost times the discounted sum of production quantities :

$$
C = q_0 \frac{LC}{1-\delta} + \delta \frac{LC}{1-\delta}(q_1 - q_0) + ... = LC \sum_{t=0}^{+\infty} \delta^t q_t
$$

Simplified approaches to get an abatement cost

The abatement cost of the substitution of an existing polluting technology (index 2) by a low-carbon technology (index 1) is evaluated as follows:

- compute the levelized costs associated with the two technologies : LC_1 and LC_2,
- determine the quantity of emissions avoided each year A
- the abatement cost AC is as follows:

$$AC=(LC_1-LC_2)/A.$$

We use two approaches to evaluate the AC for the deployment of the FCEV:

- the *static approach* does not consider the evolution of costs and compute the abatement cost associated to a vehicle each year given the costs of that year;

- a *dynamic approach* that considers the whole deployment as an investment spread over 35 years, from 2015 to 2050, in a fleet of vehicles that starts functioning and abating emissions from 2050 and implies a yearly cost to operate and renew the fleet. The dynamic approach consists in computing the abatement cost of the whole deployment.

The relevance of the dynamic approach could be understood by considering the choice of the optimal launching date of the project of deployment. It first requires describing formally the deployment:

- There is a fleet of n vehicles.
- The deployment takes T years with replacing k_τ ICE vehicles by k_τ FCEV vehicles in period τ of the deployment.
- The investment cost in the infrastructure is denoted s_τ.
- The cost of use of an ICE vehicle depends at date t is $c_{ICE,t}$; the cost of use of a FCEV vehicle depends on τ, the stage of the deployment, it is $c_{FCEV,\tau}$. After T years the cost of use of a FCEV vehicle is assumed to be stabilized *at* $\underline{c}_{FCEV}$.
- Concerning CO2 emissions, the CO2 price is p_t, and at each stage of the deployment the abatement is the difference between the emissions from an ICE vehicle $e_{ICE,t}$ and the emissions from a FCEV vehicle $e_{FCEV,\tau}$, times the number of FCEV. At the end of the deployment the emissions of FCEV are stabilized at $\underline{e}_{FCEV}$. Therefore, abatement in year t in stage τ of the deployment is

$$a_{t,\tau}=k_\tau\,(e_{ICE,t}-e_{FCEV,\tau}).$$

Let us denote I_0 the cost of the deployment if started in date 0:

$$I_0 = \sum_{t=0}^{T-1} \delta^t [s_t + k_t (c_{FCEV,t} - c_{ICE,t})].$$

This is precisely the total cost of investment for the whole deployment up to date T as computed in table 2.

Under some simplifying assumptions to be detailed shortly we shall show that the "dynamic" abatement cost at date T associated with this deployment can be written as $[(1-\delta)I_0 / \delta^T + n(\underline{c}_{FECV} - c_{ICE,T})]/A$ in which $A=n(e_{ICE,T} - \underline{e}_{FCEV})$ denotes the avoided emissions at full deployment.

This expression can be interpreted as a generalization of the static formula in which a once and for all investment with a capex of I_0 / δ^T at date T, an investment with an infinite life time, plus the difference in yearly operating costs will balance a recurring amount A of avoided emissions.

Assuming that the CO2 price p_t evolves as the social discount rate, the dynamic abatement cost evaluated at date 0 is $\delta^T[(1-\delta)I_0 / \delta^T + n(\underline{c}_{FECV} - c_{ICE,T})]/A = (1-\delta)I_0 /A + n\delta^T(\underline{c}_{FECV} - c_{ICE,T})/A$ which corresponds to the lower limit in table 2.

To obtain this result we proceed as follows. Consider the choice of the launching date. If the deployment starts today the overall cost is:

$$C_0 = \sum_{t=0}^{T-1} \delta^t p_t [(n-k_t) e_{ICE,t} + k_t e_{FCEV,t}] + \sum_{t=0}^{T-1} \delta^t [(n-k_t) c_{ICE,t} + k_t c_{FCEV,t} + s_t]$$
$$+ \sum_{t=T}^{+\infty} \delta^t n(p_t \underline{e}_{FCEV} + \underline{c}_{FCEV})$$

It is the sum of the cost of CO2 emissions during the deployment, the cost of vehicles and the infrastructure during the deployment, and the cost of the FCEV fleet including emissions once the deployment is finished. Rearranging terms:

$$C_0 = \sum_{t=0}^{T-1} \delta^t n(p_t e_{ICE,t} + c_{ICE,t}) + \sum_{t=T}^{+\infty} \delta^t n(p_t \underline{e}_{FCEV} + \underline{c}_{FCEV})$$
$$+ \sum_{t=0}^{T-1} \delta^t [s_t + k_t (c_{FCEV,t} - c_{ICE,t})] - \sum_{t=0}^{T-1} \delta^t p_t a_{t,t}$$

The second line is precisely I_0 , i.e. the cost of the deployment if started in date 0, minus the benefit from interim abatement.

If the investment starts a year later, a similar decomposition gives:

$$C_1 = \sum_{t=0}^{T} \delta^t n p_t (e_{ICE,t} + c_{ICE,t}) + \sum_{t=T+1}^{+\infty} \delta^t n(p_t \underline{e}_{FCEV} + \underline{c}_{FCEV})$$
$$+ \sum_{t=1}^{T} \delta^t [s_{t-1} + k_t (c_{FCEV,t} - c_{ICE,t-1})] - \sum_{t=1}^{T} \delta^t p_t a_{t,t-1}$$

And we can introduce the cost of deployment in that case:

$$I_1 = \sum_{t=1}^{T} \delta^t [s_{t-1} + k_{t-1} (c_{FCEV,t} - c_{ICE,t-1})] = \delta \sum_{t=0}^{T-1} \delta^t [s_t + k_t (c_{FCEV,t+1} - c_{ICE,t})]$$
$$= \delta I_0 + \sum_{t=0}^{T-1} \delta^t k_t (c_{ICE,t+1} - c_{ICE,t})$$

Compared to I_0, the deployment is launched one year later (so the discount factor), and the ICE vehicles are replaced one year earlier (so the index "t+1").

The cost to wait one year can be computed as

$$C_1 - C_0 = -[I_0 - I_1] + \delta^T n[p_T (e_{ICE,T} - \underline{e}_{FCEV}) - n(\underline{c}_{FCEV} - c_{ICE,T})]$$
$$+ \sum_{t=0}^{T-1} \delta^t p_t a_{t,t} - \sum_{t=1}^{T} \delta^t p_t a_{t,t-1}$$

Waiting one year to launch the project creates i) a financial gain by postponing investment, ii) a cost due to higher emissions in year *T* minus the relative cost of a full FCEV fleet and iii) a cost (or benefit) due to the difference between interim abatements.

For simplicity three assumptions shall be made. First, we assume that the cost of ICE vehicles evolve slowly, $c_{ICE,t} \approx c_{ICE,t+1}$, so that $I_1 = \delta I_0$. Second, the emissions intensity of ICE is nearly constant $e_{ICE,t} \approx e_{ICE,t+1}$.Third, as already introduced, the CO_2 price evolves as the social discount rate i.e. $p_t = p_0/\delta^t$.

With these assumptions the difference between the abatement benefits are null because abatement has the same value whether it takes place at t or t+1 and same abatement is done with the two options but with a one year delay:

$$\sum_{t=0}^{T-1}\delta^t p_t a_{t,t} - \sum_{t=1}^{T}\delta^t p_t a_{t,t-1} = \sum_{t=0}^{T-1}\delta^t p_t a_{t,t} - \sum_{t=0}^{T-1}\delta^{t+1} p_{t+1} a_{t+1,t} = p_0 \sum_{t=0}^{T-1}(a_{t,t} - a_{t+1,t})$$
$$= p_0 \sum_{t=0}^{T-1} k_t (e_{ICE,t} - e_{ICE,t+1}) = 0$$

Consequently the project should be launched today if and only if:

$$p_T > \frac{1}{n(e_{ICE,T} - \underline{e}_{FCEV})}\left[(1-\delta)I_0 / \delta^T + n\underline{c}_{FCEV} - nc_{ICE,T}\right] = \frac{LC_{FCEV} - LC_{ICE}}{A}$$

This gives the expected result for the dynamic abatement cost.

Summarizing the results we have two simplified approaches to assess the cost of abatement of FCEV relative to ICE: a static yearly indicator, which we expect to be decrease rapidly due to decreasing costs (in manufacturing FCEV, infrastructure and H2 production), a dynamic indicator in which FCEV substitute ICE at the horizon 2050. In the main part of the study we have provided estimates for these indicators for the base case, and discussed their sensitivity to various hypotheses.

Implicit cost of carbon: wind and photovoltaic technologies in Germany

It is interesting to compare the FCEV abatement cost not only to the normative cost of carbon as defined in section c above but also the abatement costs of other carbon free technologies.

The paper "The Cost of Abating CO2 Emissions by Renewable Energy Incentives in Germany", by C. Marcantonini and A. D. Ellerman (2013) analyzes the German experience in promoting Renewable Energy (RE) over the past decade to identify the ex-post cost of reducing CO2 emissions through the promotion of wind and solar. The authors calculated the annual CO2 abatement cost for the years 2006-2010 as the ratio of the net cost over the CO2 emission reductions resulting from the use of RE. The quantity of CO2 abated as a result of injections of wind and solar energy for the years 2006-2010 was estimated by Weigt et al. (2012) using a deterministic unit commitment model of the German electricity system.

The net cost is given by the sum of the costs and cost savings due to the injection of renewable energy into the electric power system. Other benefits -whether they are expressed as energy security, innovation, jobs, non-CO2 emissions, etc.- are not included, nor are costs associated with transmission and distribution. The costs are: the remuneration to RE generators (which depends on the RE incentives), the additional cycling costs of conventional thermal generation and the additional balancing cost (Pérez-Arriaga and Batlle, 2012). Additional cycling costs and additional balancing cost are due to the intermittency of wind and solar energy. The cost savings are: the fuel cost saving, the carbon cost saving and the capacity saving. Priority access to the grid and near- zero variable costs of RE generation means that when available renewable generation nearly always displaces conventional fossil fuel generation, typically either coal or natural gas. The fuel cost saving is the saving in the cost of the fossil fuel required to generate the electricity thus displaced, and the carbon cost saving is the saving in the cost to acquire the carbon allowances in the EU ETS for the CO2 emissions displaced. Increasing renewable generation means also increasing generation capacity in the system. Even if, because of intermittency, 1MW of nominal wind(solar) capacity it is not equivalent to 1MW of conventional generation, however wind(solar) capacity can substitute an amount of conventional capacity as much as the wind(solar) capacity credit, without exposing the system to additional risks.

As the paper develops an ex-post assessment, the impact of the subsidies (i.e. Feed In tariffs) is considered. The relevant law in Germany provides producers of RE a 20-year guaranteed fixed FIT. Since the level of the FIT diminishes in value over time both in nominal and real terms, taking the amount paid for the FIT in a given year would make wind energy appear more expensive in the first years of activities, when the payments are relatively generous, and cheaper in the following years. Consequently, the structure of payments over time requires some equalization to avoid over- and understating cost in the early and later years of the facilities life.

Methodology:

- the authors assume a 25-year lifetime for all solar and wind power plants and estimate remuneration for each vintage based on observed wind or solar generation in each year through 2010 assuming equal annual capacity factors for each in-service vintage and based on an assumed capacity factor for the remaining years of activity of that vintage;
- that stream of payments is discounted at the fixed rate of 7% and summed to get an initial Net Present Value (NPV) of all the remunerations;
- the equalized remuneration for all turbines in a given year consists of the sum of the equalized payments to each vintage of capacity in service that year.

The following table summarizes the results of the model.

Abatement costs for Wind and solar, from Marcantonini and Ellerman (2013, Table8)

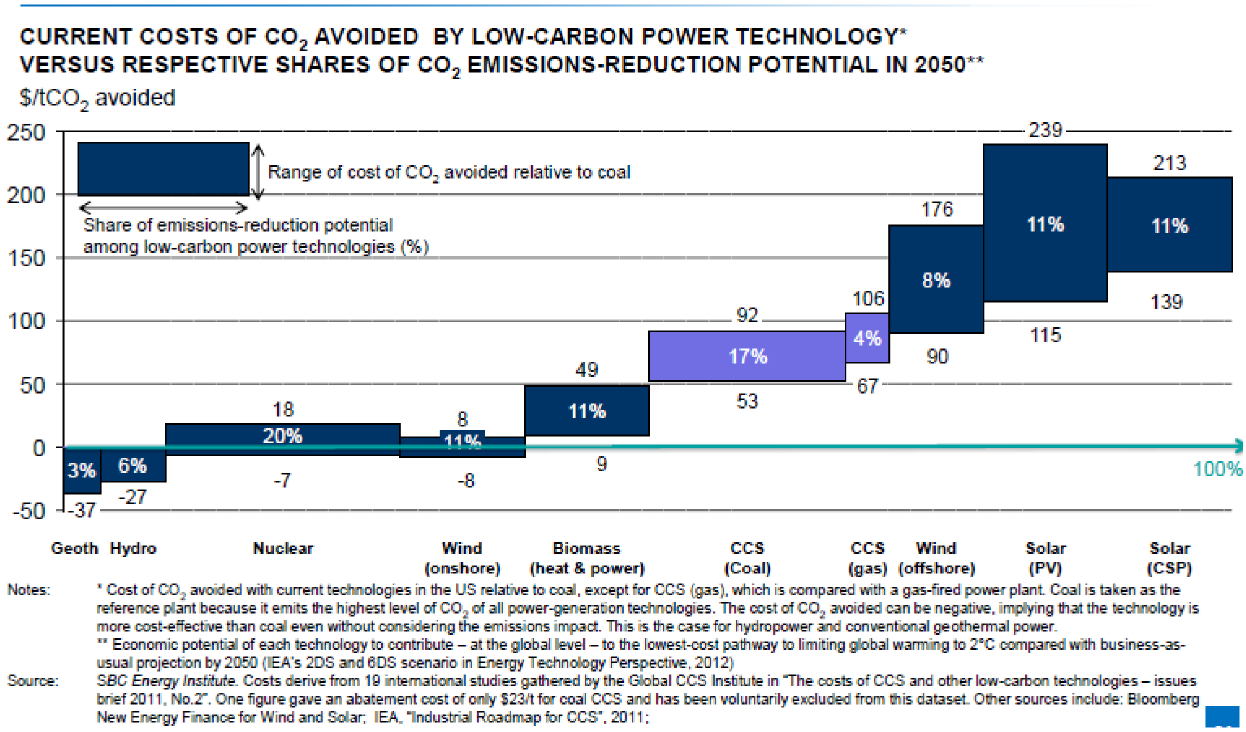
Wind		2006	2007	2008	2009	2010	Average
Equalized remuneration	[M€]	2676	2864	3047	3281	3476	
Additional start-up cost	[M€]	-6	-14	-5	2	4	
Additional balancing cost	[M€]	61	79	81	77	76	
Fuel cost saving	[M€]	-1204	-1578	-1913	-1326	-1352	
Carbon cost saving	[M€]	-381	-31	-438	-402	-402	
Capacity saving	[M€]	-106	-117	-130	-145	-158	
Net cost	[M€]	1017	1178	616	1461	1615	
CO2 emission reduction	[MtCO2]	22	26	32	30	27	
Abatement cost	**[€/tCO2]**	**47**	**47**	**20**	**50**	**62**	**44**

Solar		2006	2007	2008	2009	2010	Average
Equalized remuneration	[M€]	966	1351	1893	2882	4503	
Additional start-up cost	[M€]	-2	-3	-1	-10	0	
Fuel cost saving	[M€]	-107	-124	-212	-234	-417	
Carbon cost saving	[M€]	-28	-1	-81	-65	-113	
Net cost	[M€]	829	1223	1599	2574	3973	
CO2 emission reduction	[MtCO2]	2	2	4	5	7	
Abatement cost	**[€/tCO2]**	**552**	**627**	**439**	**557**	**547**	**537**

Three main points can be drawn.

1. There is a large disparity among different costs and cost savings.
2. There is a large difference between the abatement costs of wind and solar energy.
3. CO2 abatement cost can change considerably from year to year, particularly for wind where variations by a factor of two can be observed. These changes in net cost mostly reflect changes in annual fuel cost saving and carbon cost saving, which are correlated with variations of fossil fuel prices and the carbon price.

Other values for abatement costs and implicit cost of carbon can be calculated. As an example, the graph below displays some figures by ranking several abatement technologies (SBC Energy Institute, 2013).



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